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[Part of Vol. 19]

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L. E. WHITTEMORE, Physicist

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Bureau of Standards

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A STUDY OF RADIO SIGNAL FADING.

By J. H. Dellinger, L. E. Whittemore, and S. Kruse.

ABSTRACT.

During the years 1920 and 1921 a study was made of the variations of intensity of received radio signals of high frequency or short wave length. The investigation was conducted with the assistance of the American Radio Relay League. During the tests from 5 to 10 radio stations transmitted signals in succession. These signals were received simultaneously at about 100 receiving stations, whose operators were provided with forms for recording the variation in the intensity of the signals as received. Particular attention was given to the intensity of signals, the fading of signals, the prevalence of strays or atmospheric disturbances, and the weather conditions existing at the time of transmission. An analysis was made of the reports received, and summary tables are given which point out possible relationships between the received signal intensity, fading and strays, and the weather conditions existing at the time.

It is concluded that the sources or causes of fading are intimately associated with conditions at the Heaviside surface, which is a conducting surface some 60 miles above the earth. Daytime transmission is largely carried on by means of waves moving along the ground, while night transmission, especially for great distances and short waves, is by means of waves transmitted along the Heaviside surface. Waves at night are thus free from the more uniform absorption encountered in the daytime, but are subject to great variations caused by irregularities of the ionized air at or near the Heaviside surface. These variations probably account for fading.

CONTENTS.

I. INTRODUCTION.

1. FADING.

One of the greatest difficulties encountered in radio communication at very high wave frequencies, or short wave lengths, is the so-called "fading" or "swinging" of the received signals. For the purposes of this discussion fading may be defined as rapid variation of intensity of the signals received from a given transmitting station, all circuit adjustments at the transmitting and receiving stations remaining constant.

A number of distinctions between the uses of the terms "fading" and "swinging" have been suggested by various people. One such proposal is that fading should be classed as that type of the phenomenon in which the signal varies in intensity without variation of wave frequency, whereas swinging should designate that form in which the signal may be recovered or retuned by adjustment of the receiving apparatus. While it is probable that the two types do exist, it is difficult to distinguish between them, and they may occur simultaneously. In this discussion no distinction has been made, and the term "fading" is used according to the definition given above.

2. EXAMPLE OF FADING.

As a typical example of fading, suppose that a radio laboratory at Washington were listening to a station in Massachusetts. This station may call and be received with satisfactory intensity, may begin the preamble of the message, and then, as the text is begun, the signals may rapidly increase in intensity, until within a few seconds they may be heard throughout an ordinary room. Then, as the transmission proceeds, the signals may become rapidly weaker until they are unreadable, or even entirely inaudible by the time the end of the message is reached. By the time the station has finished the transmission of the message the signals may again be received at a satisfactory intensity. It can readily be seen that such an occurrence makes communication very difficult and may occasion many repetitions of transmissions which, if the maximum intensity were maintained, could be received without difficulty at the first attempt.

3. OCCURRENCE OF FADING.

Casual observation shows that fading is much more pronounced on the shorter wave lengths, and, in fact, there is little fading on

wave lengths greater than 400 m. When fading does occur on these longer wave lengths, the variations are much less in amplitude and far less erratic than those which occur on the shorter wave lengths. Fading does not ordinarily take place within the daylight or reliable range of the transmitting station. It is primarily a phenomenon noted at long distances from the transmitter, and hence is more prevalent during the night time, when transmission ranges are greatest.

4. WHY INVESTIGATION IS DESIRABLE.

A considerable number of papers discussing radio transmission phenomena have appeared in the radio literature of the past 10 years.[1] These have, however, been chiefly concerned with transmission at longer waves than those included in the present study, which were from 200 to 375 m. The large number of variables involved makes any radio-transmission study a difficult problem. Results can only be considered conclusive, therefore, when they are corroborated by the observations of a large number of observers and confirmed by successive investigations.

Very little commercial radio communication has been attempted on short wave lengths, and, since most of the commercial communication is carried on within the daylight ranges of the stations, fading has not been a serious obstacle to commercial development. During the past few years, however, the use of the shorter wave lengths has been on the increase not only in amateur practice, but also on aircraft, in military maneuvers, in low-power ship communication, and more recently in the broadcasting of market and general information, entertainment, and the like by radio telephone.

5. PURPOSE OF INVESTIGATION.

It has thus seemed desirable to carry out a rather comprehensive attempt to find some explanation as to the causes of fading with the hope that if the cause is known some means of avoiding the difficulty may be found.

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[1] The following papers are among the important contributions to the experimental study of radio transmission phenomena:

L. W. Austin, Long distance radio communication. Jour. Franklin Inst., **193**, pp., 437–459, April, 1922.

T. L. Eckersley, Effect of the Heaviside layer upon the errors of direction finders, Radio Rev., **2**, pp. 60–65, February, and pp. 231–248, May, 1921.

C. A. Culver, Transatlantic radio reception. Jour. Franklin Inst., **187**, p. 529, May, 1919.

A. H. Taylor and A. S. Blatterman, Variations in nocturnal transmission, Proc. I. R. E., **4**, p. 131, April, 1916.

E. W. Marchant, Conditions affecting the variations in strength of wireless signals. Electrician, **74**, p. 621, Feb. 12, 1915.

W. H. Eccles, Atmospheric refraction in wireless telegraphy. Electrician, **71**, p. 969, Sept. 19, 1913.

II. PLAN OF INVESTIGATION.

1. BEST METHODS.

Considerations of the possible methods of conducting such an investigation lead to the conclusions that they should take place on short wave lengths where fading is most pronounced, and that a large number of observations should be taken by many observers. It follows at once that the cooperation of a large number of well-equipped amateur stations, whose operators are familiar with their apparatus and also with communication on short wave lengths, offers an excellent source of material for such an investigation. The amateur operator is also more apt to be able to devote his time and effort toward obtaining the required information.

2. PRELIMINARY PLAN.

(*a*) CONFERENCE.—With these facts in mind a tentative plan was worked out in the spring of 1920, in which the stations of The American Radio Relay League would do the transmitting and the observing, while the supervisory and clerical work and the analysis of the data would be performed at the Bureau of Standards. Laboratory tests of methods of recording variations in signal intensity indicated that worth-while results could be secured without the use of any instruments other than the regular receiving equipment. The Bureau of Standards then proposed the plan to The American Radio Relay League. The proposals were received favorably and plans were completed at a conference at the Bureau of Standards radio laboratory on April 7, 1920,[2] at which there were present: For The American Radio Relay League, H. P. Maxim and K. B. Warner, and for the Bureau of Standards, Dr. J. H. Dellinger, L. E. Whittemore, and S. Kruse; Commander A. H. Taylor, U. S. N. R. F., in charge of the radio laboratory, Naval Air Station, Anacostia, D. C., and Dr. S. J. Mauchly and A. Sterling, of the Department of Terrestrial Magnetism, Carnegie Institution, Washington, D. C., were also present and offered valuable suggestions. The tentative plans were brought into a workable shape and the transmitting stations agreed upon.

During the following weeks the officers of The American Radio Relay League selected recorders who were properly located with respect to the transmitting stations and who were believed to be well equipped as to apparatus and experience and who could also find the time to take part in the tests.

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[2] See Bureau of Standards ARRL tests of short-wave radio signal fading, S. Kruse; "QST," November, 1920, p. 5, and December, 1920, p. 13.

(*b*) General Outline of Plan.—The general plan was to have these recorders make simultaneous records of each of several transmitting stations operating according to a prearranged schedule. The results of these observations were to be forwarded periodically to the Bureau of Standards, where the analysis was to be made.

(*c*) Preliminary Tests.—In order to test the practicability of the method and to locate any serious discrepancies in the procedure as outlined, a preliminary test was arranged for the months of June and July, 1920. The results of this test gave much valuable information in regard to the conducting of the future tests.[3]

3. DESCRIPTION OF GENERAL PLAN.

(*a*) Schedule of Series of Tests.—At a later conference with the national officers of The American Radio Relay League these data were discussed and general plans made for the future tests. It was decided to hold three additional tests, each extending through one month, and each to occur at a different season of the year, the preliminary test to stand as representative of summer-month conditions. These four series will be repeatedly referred to and are therefore here tabulated for convenience:

Season.	Month.	Year.	Name of series.
Summer	June and July	1920	July, or first.
Fall	October	1920	October, or second.
Winter	January	1921	January, or third.
Spring	April	1921	April, or fourth.

Several special tests were also conducted and will be referred to later. These tests were: (1) Special "sunset test" sent by the regular stations of the October series on October 17, 1920; (2) special "noon test" sent by the regular stations of the October series on October 24, 1920; (3) special tests sent by 8XK, Pittsburgh, Pa., October 26 and 28 (called A, B, C, and D).

The station network used during the tests consisted of 17 sending stations and 243 recorders. This network was changed in certain respects during the year required for the completion of the observations, as will be noted below. The descriptions of the sending and receiving stations are also given below.

(*b*) Criticisms of Plan.—Considerable criticism of the investigation was occasioned by the fact that only the northeast portion of the United States was covered in the tests. There were several

[3] See footnote 2, p. 197.

reasons for so confining the observations, among the more important ones being the entire lack of suitable stations in the southeast part of the country and the scarcity of stations in the southwest and northwest portions, where very great distances would have to be covered. There also appeared at that time to be a limit to the number of observations and variable factors which could be handled and adequately analyzed. Somewhat greater spacing of recording stations west of Pittsburgh was allowed because it was believed that the ranges in the Mississippi Valley were considerably greater than in the North Atlantic States. The fact that there was a vast difference between the winter and summer range in the midwest was not recognized, however, and thus the wider spacing of the recording stations in this district placed a handicap upon the operation of the sending stations 9ZN at Chicago and 9LC at St.Louis. This necessitated the placing of station 8ER at St. Marys, Ohio, upon the transmitting schedule.

(c) DESCRIPTIONS OF SENDING STATIONS.—*1AW, Hartford, Conn., H. P. Maxim, pres., American Radio Relay League.*—One kilowatt, 60-cycle spark, with a nonsynchronous discharger working at 480 sparks per second. Antenna height, 80 feet; current, 5 amperes. Wave lengths used during tests, 215 and 250 m.

1BBL, Farmington, Conn., David L. Moore.—One kilowatt, 60-cycle spark, with a nonsynchronous discharger working at 300 sparks per second. Antenna height, 50 feet; current, 5 amperes. Wave length used during the tests, 300 m.

2RK, Brooklyn, N. Y., John K. Hewitt.—One kilowatt, 60-cycle spark, with synchronous discharger working at 240 sparks per second. Antenna height, 80 feet; current, 5 amperes. Wave lengths used during tests, 250 and 375 m.

2JU, Woodhaven, Long Island, C. J. Goette.—One kilowatt, 60-cycle spark, with synchronous discharger working at 240 sparks per second. Antenna height, 80 feet; current, 5 amperes. Wave lengths used during tests, 250 and 375 m.

2ZL, Valley Stream, Long Island, J. O. Smith.—Two General Electric 50-watt, type "U" tubes with 60-cycle alternating current as plate voltage. (This station substituted for 2RK, Brooklyn, N. Y., on one schedule.)

NSF, Anacostia, D. C., Naval Air Station, radio laboratory, in charge of Commander A. H. Taylor; operator, Radio Aide L. C. Young.—Two General Electric type "P" tubes with continuous

current supply from generator. These tubes act as power amplifiers, the master oscillator being a Western Electric type "E" tube, modulated by another similar tube upon whose grid is impressed 1,000 cycle alternating current from a microphone buzzer. The antenna is multiple tuned, 85 feet high, 235 feet long, the total current in the three down leads being 9 amperes. Wave lengths used during tests, 200, 250, and 375 m.

WWV, Washington, D. C., Bureau of Standards radio laboratory, in charge of Dr. J. H. Dellinger; operator, S. Kruse.—Two General Electric type "P" tubes with continuous current supply from a generator. Modulation by a motor-driven chopper in series with grid-leak resistance. Antenna height, 80 feet; current, 5 amperes. Wave length used during tests, 200 m.

3XF, Washington, D. C., Francis M. Baer.—One kilowatt, 60-cycle spark, with a nonsynchronous discharger worked at 480 sparks per second. Antenna height, 70 feet; current, 4.5 amperes. Wave lengths used during tests, 250 and 375 m.

3ZW, Washington, D. C., W. A. Parks.—One kilowatt, 60-cycle spark, with a nonsynchronous discharger. (This station substituted for NSF on one schedule.)

8XK, Pittsburgh, Pa., F. Conrad.—Two General Electric type "U" tubes with an alternating current plate supply of 3,000 volts at 700 cycles. Antenna height, 50 feet; current, 5.5 amperes. Wave length used during tests, 250 m.

8ZW, Wheeling, W. Va., John C. Stroebel, jr.—One kilowatt, 60-cycle spark, with a nonsynchronous discharger, operated at 360 sparks per second. Antenna height, 55 feet; current, 8 amperes. Wave length used during tests, 250 m.

8ER, 8ZL, St. Marys, Ohio, Mr. and Mrs. Charles Candler.—One kilowatt, 60-cycle spark, with a nonsychronous discharger worked at 300 sparks per second. Antenna height, 57 feet; current, 5 amperes. Wave length used during tests, 250 m.

9ZJ, Indianapolis, Ind., F. F. Hamilton.—One kilowatt, 300-cycle spark, with a nonsynchronous discharger working at 210 sparks per second. Antenna height, 60 feet; current, 7.5 amperes. Wave lengths used during tests, 200 and 375 m.

9LQ, Indianapolis, Ind., C. W. Dean.—One kilowatt, 60-cycle spark, with a nonsynchronous discharger worked at 120 sparks per second. Antenna height, 55 feet; current, 5 amperes. Wave length used during tests, 250 m.

9ZN, Chicago, Ill., Chicago Radio Laboratory; operators, R. H. G. Mathews, C. Hassel, D. N. Buck, and George A. Fitzsimmons.—Two

kilowatt, 60-cycle spark, with a synchronous discharger operated at 120 sparks per second. Antenna height, 80 feet; current, 6 amperes. Wave length, 375 m. Two kilowatt, 500-cycle spark, with a quenched gap, operated at 1,000 sparks per second. Antenna height, 80 feet; current, 13 amperes. Wave length 375 m. During the April tests the 500-cycle set was used with a temporary antenna, height 80 feet; current, 12 amperes. Wave length, 375 m.

9AU, Chicago, Ill., C. H. Zeller.—One kilowatt, 60-cycle spark, with a nonsynchronous discharger. Antenna height, unknown; current, 3.75 amperes. Wave length used during tests, 250 m.

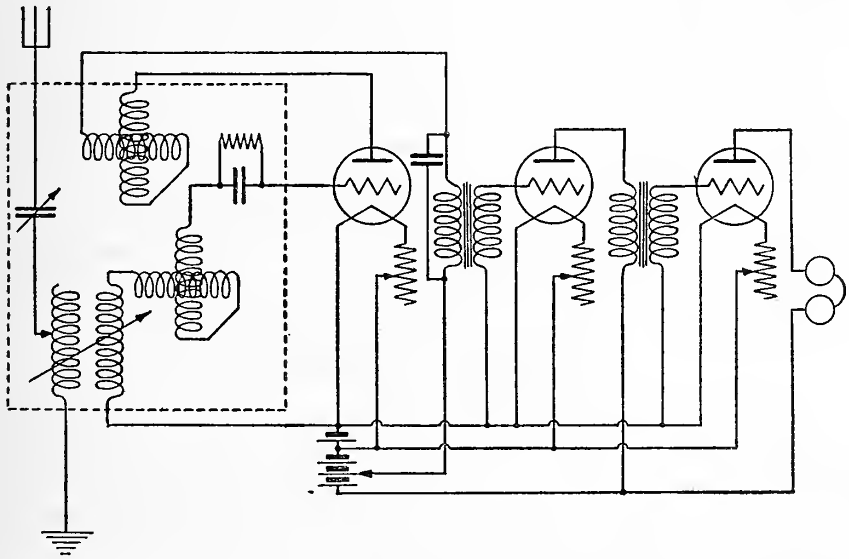


FIG. 1.—*Type of receiving circuit (tuned plate) used by majority of receiving stations taking part in these tests.*

9LC, St. Louis, Mo., W. E. Woods.—One-half kilowatt, 60-cycle spark, with a nonsynchronous discharger. Antenna height, 55 feet; current, 4.5 amperes. Wave length used during tests, 250 m.

(*d*) RECORDERS.—Two hundred and fifty-three recorders took part in the tests, although certain changes and additions were made from time to time.

(*e*) DESCRIPTION OF RECEIVING APPARATUS.—With few exceptions the recorders used that type of short-wave receiving apparatus generally known as "tuned-plate regenerative," the schematic diagram of which is shown in Figure 1. The tuning of the primary circuit is accomplished by means of a switch on the inductance and a series condenser in the antenna lead. The secondary

circuit is not tuned by means of a shunt condenser, but by means of a variable inductor in series with the secondary. A great increase in sensitiveness is secured, as the ratio of inductance to capacity in the circuit is much improved over that obtained when using a shunt condenser. The plate circuit of the tube contains another variable inductor by means of which the degree of regeneration can be controlled. For spark or ICW reception the set is usually operated with the largest degree of regeneration which will not distort the spark tone. Almost without exception the recorders used a "soft" or gas tube as the detector and "hard" or high vacuum tubes for the amplifier. Minor variations of the circuit occurred, such as the provision of taps on the B battery as a means of varying the plate voltage of the detector tube.

The recorders, with few exceptions, used four or six wire L antennas about 60 feet high and 60 feet long. These were suspended by means of insulators, and in most cases copper wire, No. 12 or thereabouts, or 7-strand phosphor bronze, was used. The ground connections in most cases were to water pipes; in some cases to buried networks. A few recorders used harp antennas. All of the transmitting operators, except the one actually sending at the time, acted as recorders.

4. SCHEDULE OF TRANSMISSION.

(*a*) Time.—All tests, with the exception of the special tests previously mentioned, were conducted at night, immediately following the transmission of time signals by Arlington (NAA) at 10 p. m. eastern standard time. This enabled the various operators to obtain the correct time and so synchronized the schedules that few errors occurred.

(*b*) Method Employed.—Special licenses were, where necessary, issued by the Department of Commerce, permitting the operation of the transmitting stations on the wave lengths as noted in the schedules below. The method of sending a particular test upon which observations were to be made was to send a long QST, followed by the call of the transmitting station and the words "Bureau of Standards ARRL fading tests." The letters of the alphabet, each repeated five times, were then sent at a rate of about 15 words per minute and the test concluded by the signature of the transmitting station. In the early tests the alphabet was only sent through once, but it soon appeared desirable to have longer periods of observation, and the alphabet was transmitted twice, first forwards and then backwards.

(*c*) Example.—A typical test would be sent as follows: "QST QST QST de 1AW 1AW 1AW Bureau of Standards ARRL fading tests Bureau of Standards ARRL fading tests de 1AW 1AW 1AW – . . . – AAAAA BBBBB CCCCC (etc.) YYYYY ZZZZZ YYYYY XXXXX (etc.) BBBBB AAAAA . . . – . – 1AW"

(*d*) Schedules of Transmitting Stations.—During the July series three tests were made each week—on Tuesday, Thursday, and Saturday evenings—the first test starting at 10.10 p. m. eastern standard time. All succeeding tests were made according to the same schedule, except that only two tests per week were attempted. The various transmitting stations followed in their order at 10-minute intervals, according to the following schedules:

Schedule of Transmitting Stations.

[Spark Stations Except as Otherwise Noted.]

JULY TEST.

Station sending.	Location.	Wave length.	Starts at (eastern standard time)—
			p. m.
1AW	Hartford, Conn	250	10.10
2JU	Woodhaven, Long Island	250	10.20
NSF	Anacostia, D. C	250	10.30
8XK	Pittsburgh, Pa	250	10.40
9ZN	Chicago, Ill	250	10.50
9LC	St. Louis, Mo	250	11.00

OCTOBER TEST.

1AW	Hartford, Conn	250	10. 10
NSF	Anacostia, D. C	250	10. 20
8ZW	Wheeling, W. Va	250	10. 30
8ER, 8ZL	St. Marys, Ohio	250	10. 40
9ZN	Chicago, Ill	250	10. 50

JANUARY TESTS.

Group A.

NSF	Relay NAA time	250	10. 00
1AW	Hartford, Conn	250	10. 10
NSF	Anacostia, D. C	([1] ICW)250	10. 20
2JU	Woodhaven, Long Island	250	10. 30
NSF	Anacostia, D. C	([1] ICW)250	10. 40
9LQ	Indianapolis, Ind	250	10. 50
9AU	Chicago, Ill	250	11. 00

Group B.

NSF	Relay NAA time	250	10. 00
1BBL	Farmington, Conn	300	10. 10
3XF	Washington, D. C	375	10. 20
2RK	Brooklyn, N. Y	375	10. 30
3XF	Washington, D. C	250	10. 40
9ZJ	Indianapolis, Ind	375	10. 50
9ZN	Chicago, Ill	375	11. 00

Schedule of Transmitting Stations—Continued.

APRIL TESTS.

Group A.

Station sending.	Location.	Wave length.	Starts at (eastern standard time)—
			p. m.
NSF	Relay NAA time	250	10.00
1AW	Hartford, Conn	200	10.10
NSF	Anacostia, D. C	([1] ICW)200	10.20
9ZN	Chicago, Ill	375	10.30
9ZJ	Indianapolis, Ind	200	10.40

Group B.

Station sending.	Location.	Wave length.	Starts at (eastern standard time)—
NSF	Relay NAA time	250	10.00
1AW	Hartford, Conn	200	10.10
WWV	Washington, D. C	([1] ICW)200	10.20
9ZN	Chicago, Ill	375	10.30
9LQ	Indianapolis, Ind	200	10.40

[1] Interrupted continuous wave.

(*e*) Discussion of Schedules.—In the July and October tests the principle object in view was to note the differences in the characteristics of the fading of signals from the various transmitting stations from a geographical standpoint; that is, by comparison of the results of observations made simultaneously in different parts of the country upon each transmitting station. In this way, for instance, it might be determined whether or not an increase in intensity to the east of a given transmitter was simultaneously accompanied by a decrease in intensity at stations to the west of the transmitter. It also might be determined whether the fading phenomenon was confined to any particular district or in any given direction relative to the transmitting station.

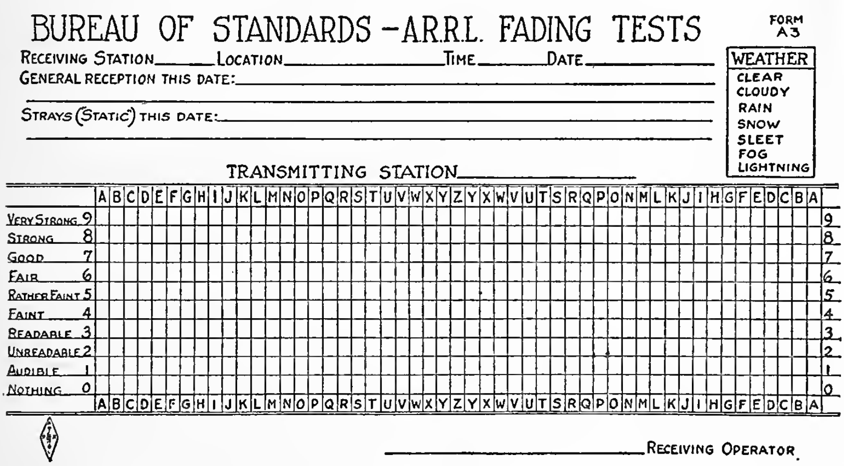
The January tests were so planned and executed that comparisons might be made between the fading characteristics of two stations in the same locality sending at the same time but on slightly different wave lengths. In this way it was believed that if fading were due to conditions adjacent to the transmitting station the observations would show simultaneous fading of the two stations.

The April tests were intended to make still further refinements in the attempt to isolate the cause of the fading. In this series the transmitting was done by two stations operating simultaneously and on the same wave length but each with a distinctive spark note, so that observations could be made without difficulty.

5. METHOD OF RECORDING.

(*a*) Methods Considered.—Considerable attention was given to possible methods of recording the variations in signal intensity as observed at the recording stations. Among the methods considered were: (1) Measuring instruments to be inserted in the telephone circuits, (2) phonographic recorders, (3) audibility meter measurements, (4) audibility measurements by comparison methods, and (5) aural reception and recording of intensity variations on forms to be provided for the purpose.

(*b*) Method Adopted.—The first four of these methods had to be rejected because of the impossibility of providing all of the observers with the necessary apparatus, in addition to the many


BUREAU OF STANDARDS - A.R.R.L. FADING TESTS

FORM A3

RECEIVING STATION ____ LOCATION ____ TIME ____ DATE ____

GENERAL RECEPTION THIS DATE: ____

STRAYS (STATIC) THIS DATE: ____

WEATHER: CLEAR, CLOUDY, RAIN, SNOW, SLEET, FOG, LIGHTNING

TRANSMITTING STATION ____

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z Y X W V U T S R Q P O N M L K J I H G F E D C B A

VERY STRONG 9; STRONG 8; GOOD 7; FAIR 6; RATHER FAINT 5; FAINT 4; READABLE 3; UNREADABLE 2; AUDIBLE 1; NOTHING 0

____ RECEIVING OPERATOR

Fig. 2.—*Record form used by fading-test observers.*

other obvious objections to them. The fifth method, the one adopted for the tests, was shown to be qualitatively accurate in recording intensity variations by actual tests, both in the laboratory and in actual transmission. A form provided for the recording of the signals during the tests is illustrated in Figure 2.

(*c*) Examples of Accuracy.—Figure 3 shows a test of the method under operating conditions, the two curves being the records of the variations in signal strength of station 2JU, Brooklyn, N. Y., as observed at Hartford, Conn., by H. P. Maxim and K. B. Warner, who were listening with separate telephones connected to the same receiving set. It will be seen that although each observer judged the actual intensity somewhat differently the variations are qualitatively the same. A similar test made in the laboratory on buzzer signals artificially varied in intensity is

shown in Figure 4. These curves are also an indication that the method is satisfactory for recording the variations in signal strength.

(*d*) Method Used in Practice.—In practice the observers were provided with copies of the recording forms and with schedules of the transmitting stations. During the January and April tests approximately half of the observers were assigned to record the

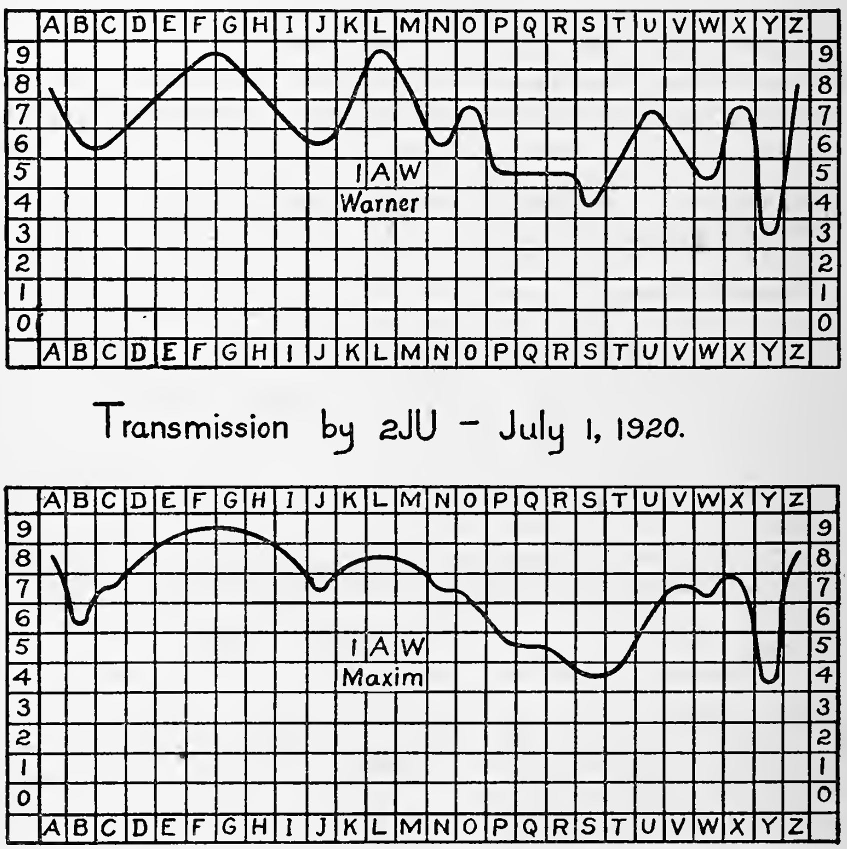


Fig. 3.—*Similar curves obtained by two operators at the same receiving station.*

signals of the Group A transmitting stations and the other half to the Group B transmitting stations. (*See* Schedule of transmitting stations, p. 203.) The observer was instructed to tune in the signals during the preamble transmitted before the actual test and then to leave the adjustments strictly constant throughout the remainder of the test period. He was further instructed to estimate the signal intensity according to the arbitrary scale on the forms supplied and at the beginning of the actual test to make a series of dots or a

continuous curve representing the intensity of each letter of each group as sent by the transmitter. The other items on the forms were to be filled in at the end of the tests for the evening. One form was filled out for each transmitting schedule and turned in to the Bureau of Standards regardless of whether or not the actual transmission was recorded.

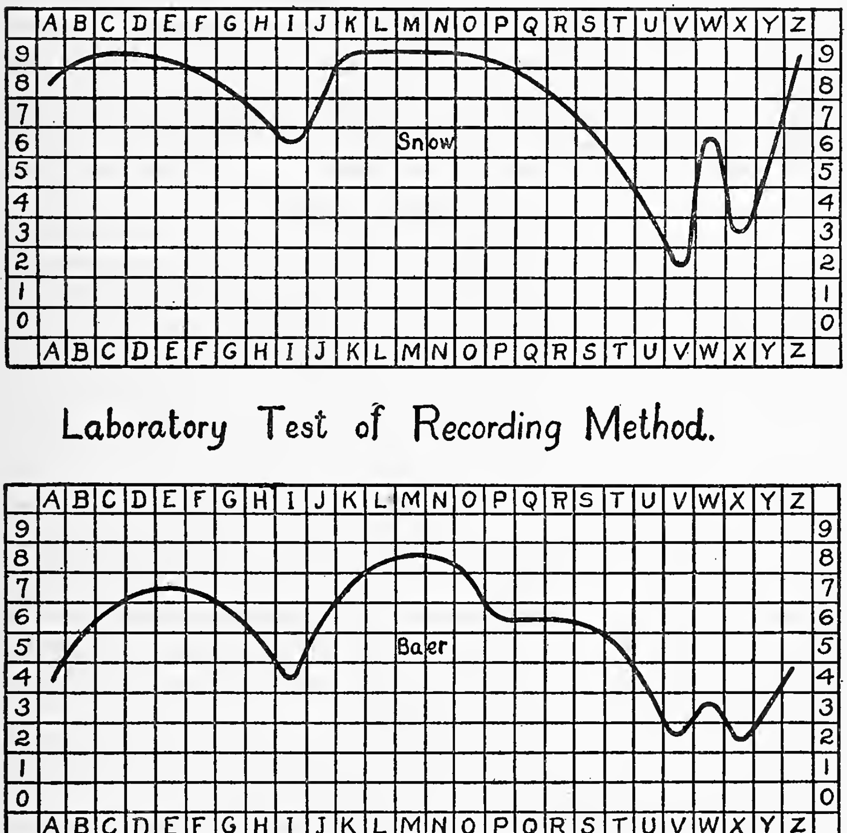


FIG. 4.—*Laboratory test of recording method.*

(*e*) RESULTS.—The records as obtained by the observers were, on the whole, very satisfactory. Interference from other stations was the most frequent source of trouble, and severe atmospheric disturbances of "static" also hindered recording. The most accurate results were undoubtedly obtained when there was no interference and when the fading was rather slow, for when rapid fluctuations occur it is difficult to estimate the intensities accurately.

(*f*) Difficulties Encountered.—It was generally observed that the best recorders were, without exception, those who had some training in measurement work and were accordingly accustomed to laboratory measurements. These observers not only became the best observers but also seemed to grasp the working of the method most promptly.

Singularly enough, the best radio operators were not generally good recorders, their curves being flat and lacking in detail, apparently because of the operator's tendency to concentrate his attention on the signal to the exclusion of all other sounds. He apparently follows the variations in signal strength without being aware that any variation is taking place.

6. REVISIONS IN PLANS.

(*a*) Changes in Transmitting Stations.—The early tests showed that there was room for improvement in many places, and changes were accordingly made from time to time. Certain of the transmitting stations selected in the early part of the investigation were unable to continue operation on the desired schedule and were replaced by other transmitting stations. The results of the July tests on station 9LC at St. Louis could not be used, as insufficient records on this station were received, due to the severe summer atmospheric conditions in the Mississippi Valley. It was necessary to select new transmitting stations for the tests during January and April because of the special nature of these tests. Certain of the recorders were also unable to continue throughout the period of the tests, and new recorders were added from time to time as seemed desirable.

(*b*) Special Tests.—The first of the special tests previously mentioned was held on October 17, during the hour of sunset, to determine the effect of the twilight upon fading. The observers were notified that the regular stations of the October series would transmit according to schedule.

The second special test occurred on October 24, just after noon, the purpose being to compare the daylight with the night fading. This test was also sent by the regular stations of the October series according to schedule.

The third of the special schedules was held on October 26 and 28 in the attempt to determine the cause of the very erratic fading noted on station 8XK at Pittsburgh, Pa. It was believed that much of the apparent fading was due to tube blocking or

similar conditions at the transmitter, and such was proved to be the case, as will be shown later. The schedules for these tests are shown below.

(*c*) Special Test Schedules.—

Special Transmitting Schedules.

SUNSET TEST, OCTOBER 17.

Station sending.	Location.	Wave length.	Starts at (eastern standard time)—
			p. m.
1AW	Hartford, Conn	250	5.30
NSF	Anacostia, D. C	250	5.40
8ZW	Wheeling, W. Va	250	5.50
8ER	St. Marys, Ohio	250	6.00
9ZN	Chicago, Ill	250	6.10

NOON TEST, OCTOBER 24.

1AW	Hartford, Conn	250	12.10
NSF	Anacostia, D. C	250	12.20
8ZW	Wheeling, W. Va	250	12.30
8ER	St. Marys, Ohio	250	12.40
9ZN	Chicago, Ill	250	12.50

8XK TESTS, OCTOBER 26.

Test A, 11 p. m., eastern standard time, 250 m.; 700-cycle plate supply.
Test B, 11.20 p. m., eastern standard time, 250 m.; 700-cycle plate supply.

8XK TESTS, OCTOBER 28.

Test C, 11 p. m., eastern standard time, 250 m.; 700-cycle plate supply.
Test D, 11.20 p. m., eastern standard time, 250 m. Master oscillator with power amplifier having 700-cycle plate supply.

III. OPERATION OF TEST.

1. DESCRIPTION OF OPERATION.

(*a*) General Discussion.—The transmitting station network performed excellently throughout the series of tests. After the first few days, in which several delays occurred, no station failed to transmit its test schedule, except on the few occasions when the cause of the failure was beyond the control of the operator.

(*b*) Average Distance of Transmission.—The average distance of transmission was approximately 400 miles, with an input power not exceeding 1 kw. in any case.

(*c*) Average Number of Recorders.—During the July tests, which were the most difficult in all respects, an average of 26 observers stood watch every evening and on no occasion were less than 20 on duty. This number was increased during the later tests, and the perseverance of the recording operators resulted in over 500 usable records which were included in the analysis.

2. JULY AND OCTOBER TESTS.

DIFFICULTIES.—During the July and October tests some trouble was encountered in the overlapping of the transmitting schedules because of delays due largely to the operators not having the correct time. Several stations were not able to tune to 2,500 m to obtain the time signals from Arlington (NAA). Beginning with the January tests the Naval Air Station at Anacostia, D. C. (NSF), received the Arlington time signals on a ground wire, amplified them, and thus modulated the high-power radiophone set. A regular schedule for this feature was arranged on a 250-m wave length, and it served to coordinate the schedules, so that thereafter very little trouble was encountered due to the lack of correct time.

3. JANUARY TESTS.

(*a*) PROBLEMS OF SYNCHRONIZING.—In the January tests, when it was desired to observe the fading of two stations in the same locality sending simultaneously, but on the same wave length, it became necessary to perfect a method of synchronizing the sending of the two stations involved. This problem was left largely to the sending stations themselves and was, in general, solved very satisfactorily.

(*b*) METHODS USED.—The signals of 1AW at Hartford, Conn., and of 1BBL at Farmington, Conn., were synchronized by ear, 1AW sending steadily and 1BBL following as closely as possible. Station 9AU, Chicago, followed 9ZN, Chicago, in the same manner with remarkable accuracy. Station 2JU, Woodhaven, L. I., also followed 2RK, Brooklyn, N. Y., by this method. 9LQ and 9ZJ, Indianapolis, were synchronized through a wire line which passed through a telephone exchange, and they were troubled occasionally by interruptions of the connection. 3XF and NSF, Washington and Anacostia, D. C., were also synchronized automatically, the signals from 3XF being received on a ground wire at NSF, amplified, and used to control the transmitting key of the NSF transmitter. The key at 3XF thus controlled both of these stations. With the exception of slight trouble due to atmospherics this system worked perfectly.

(*c*) DIFFICULTIES.—Some trouble was experienced in practice in connection with the 2JU–2RK pair, since they both had similar spark notes, and neither station seemed particularly sharply tuned. It was common to have observers alternate from one station to the other in making the records. Similar trouble also occurred in the recording of the 9ZJ–9LQ pair.

4. APRIL TESTS.

SYNCHRONIZING DIFFICULTIES.—In the April series of tests it was the intention to have the transmitting station pairs send simultaneously on the same wave length. Due to the difficulty in finding a suitable companion station, this was not carried out in the case of 1AW, at Hartford, Conn., and this station sent alone as in the first two series. NSF and WWV, Anacostia and Washington, D. C., constituted a pair, both operating on ICW with distinctive notes. The stations of this pair were sychronized by reception of the WWV signals on a ground wire at NSF, as in the previous series, and in order to obtain satisfactory operation it was found necessary to maintain a wave length difference of about 30 m. The tone difference of the two stations was almost exactly an octave, and this, together with the superior signal strength of NSF, led to some confusion in the recording. The 9LQ and 9ZJ pair at Indianapolis were also automatically synchronized in this test, and here, again, the tones of the stations were almost exactly an octave apart. The signals from 9ZJ were also much stronger than those from 9LQ and some confusion resulted.

The 9ZN–9ZN pair at Chicago was probably the best combination of the series, both sets being operated from the same key and used on different aerials. Unfortunately the combination was not ready until the test was nearly over, so that relatively few records were obtained.

5. DISCUSSION.

In all tests of this series some trouble was also experienced at the recording stations because the transmitter did not always fade simultaneously. When one station of the pair was very weak, the other station was apt to be at normal intensity, and so precluded the possibility of noting variations in strength of the weaker signal. The operation of the April tests, as in the case of the July tests, was also marred by strong atmospheric disturbances which ruined many records.

IV. ANALYSIS.

1. DATA OBTAINED.

RECORDS USED.—In sorting the records obtained by the observers only those which were nearly complete or unbroken by interference discontinuities were used. Many records were discarded because there was some doubt as to the identity of the

transmitting station, and many others were also discarded because the observer had changed the adjustments of his receiving set during the test. After this sorting had been completed there remained 5,684 cards, which were used in making the final analysis. This number is exclusive of those cards obtained as the result of the three special tests held during October.

2. METHODS OF ANALYSIS.

(*a*) PROBLEMS.—The problem of analyzing the data contained on the 5,684 cards presented innumerable difficulties not only because of the large number of observations involved, but also because of the great number of factors which undoubtedly influence the fading and which greatly complicate and confuse the data. The factors which were noted at each observation are given in the following list. Some of these were noted by the observer directly upon the recording form and other items were obtained from the weather maps of the Department of Agriculture, from the Carnegie Institution, Department of Terrestrial Magnetism, and from other sources.

Variable Factors Considered in Analysis: (1) Weather conditions at observer (clear, cloudy, rain, snow, sleet, fog, and lightning), (2) general reception date of test, (3) strays or "static" characteristics on date of test, (4) atmospheric conductivity, (5) atmospheric potential gradient, (6) presence of aurora, (7) barometric pressure, (8) temperature, (9) barometric gradient, (10) temperature gradient.

It is quite evident that if more than one of these factors has any effect upon the characteristics of the fading the data may become extremely difficult to analyze.

(*b*) DIRECT COMPARISON.—The first and simplest method of analysis consists of direct examination of the fading curves and the comparison of those curves taken simultaneously by different observers on the same transmitting station. In making such a comparison all the cards received as records of one transmission from a given transmitting station were laid out on a large table. Each record was then compared with all the others in the group and an attempt was made to find characteristics common to the various records.

1. *Similar curves.*—Several characteristics of interest were obtained in this manner, although their importance is questionable. It was first noticed that similar curves occasionally occurred, and that the observers obtaining such curves might be widely sep-

arated geographically. Such a case of similarity of fading characteristics as observed in different localities is illustrated in Figure 5.

2. *Traveling curves.*—Coincidently with this type of similar curve there also frequently occurred what has been called a "traveling curve"; that is, several curves are found which are

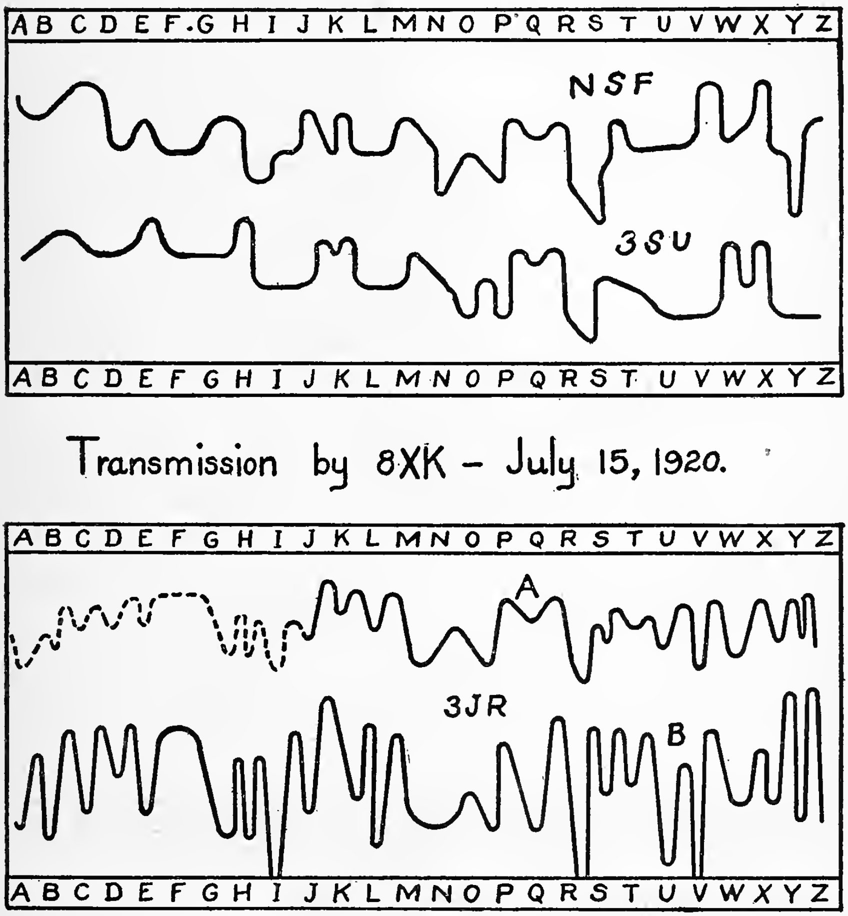


Fig. 5.—*Similar curves obtained by three Washington stations.*

similar in appearance, except that the variations in intensity occur at different times at the different stations (fig. 6). In general, this effect seems to occur very haphazardly as regards the geographical distribution of the stations concerned, and therefore few, if any, conclusions can be drawn from their occurrence.

Out of the 5,684 observations there were found 380 similar pairs of curves, including in this category the traveling curves.

This represents only 6.7 per cent of the total, and since such cases occurred very erratically it is doubtful if there is anything more than an accidental connection between the curves. As an example of this effect, it was noticed that of the observations on station 2RK, at Brooklyn, N. Y., on January 25, 1921, at 10.30 p. m., the following cases of similar curves resulted:

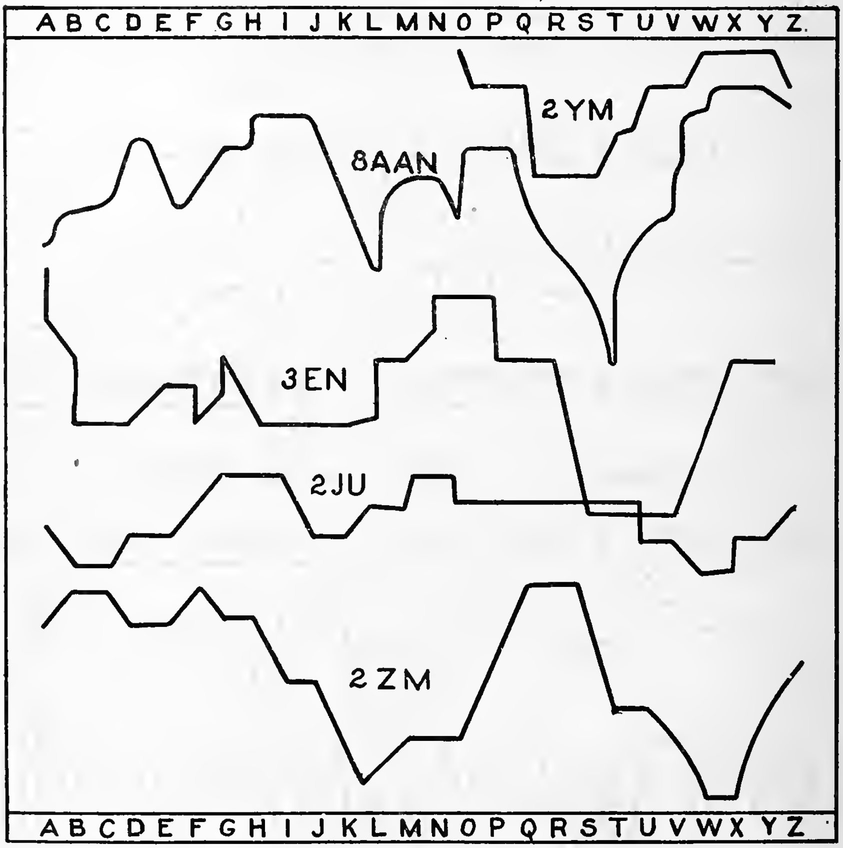


Fig. 6.—*A traveling curve. Transmission by 8XK, July 8, 1920.*

8ZV, Canton, Ohio, similar to 8ZW, Wheeling, W. Va.
8ZV, Canton, Ohio, similar to 8MT, Uniontown, Pa.
WWV, Washington, D. C., similar to 4YA, Atlanta, Ga.
2TF, Schenectady, N. Y., similar to 2AX, Standridge, Quebec.
1AK, Fall River, Mass., similar to 2TS, Bristol, Conn.
2AX, Standridge, Quebec, similar to NSF, Anacostia, D. C.
2AK, Fall River, Mass., similar to 4CK, Winston-Salem, N. C.

It should be noted that in the case of the first five pairs in this list the members of each pair are in the same general direction from the transmitting station. The sixth pair are at a wide angle apart relative to the transmitter, and the last pair are almost

exactly at a 180° angle, or in opposite directions from the transmitter. In addition to the above observations there were obtained during this same transmission 30 records which exhibited no common similarities. Many of these records were taken at points within a few miles of members of the pairs in the above lists, and yet these curves are entirely unlike those obtained by the other close-by observers. Of the 380 pairs of similar curves obtained

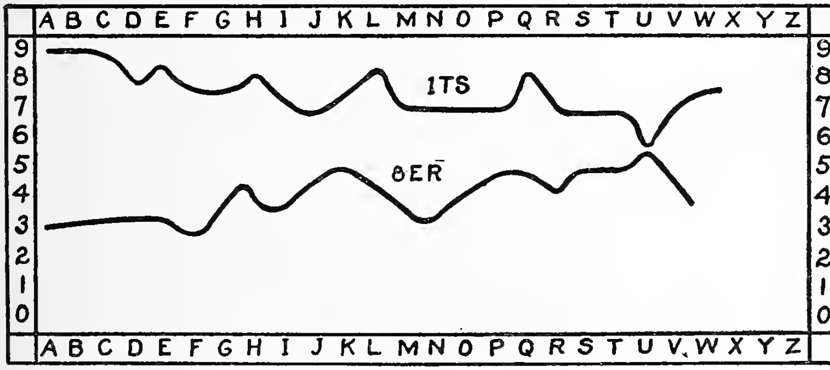


FIG. 7.—*Inverse curve. Transmission by 8XK, July 3, 1920.*

it is interesting to make a classification according to the general direction of the pair from the transmitter.

Summary of Similar Pairs.

Total similar pairs	380
Per cent of total observations	6.72
Number of similar pairs in same general direction from transmitter (within 45° angle)	258
Per cent of similar pairs	68.02
Number of pairs in opposite direction from transmitter (within 45° of 180° angle)	34
Per cent of similar pairs	9.0
Number of pairs at intermediate angles from transmitter	88
Per cent of similar pairs	23.02

(3) *Inverse curves.*—Another peculiar curve found occasionally is that called the "inverse curve," wherein the fluctuations in signal intensity are 180° out of phase at two stations; that is, the curves are similar but opposite in sense. This type of similarity is illustrated in Figure 7. Of the 5,684 observations only 31 cases, or 0.62 per cent, of inverse curves were found, and such curves are considered to be purely accidental in their occurrence.

(*c*) MAP ANALYSIS.—Another method was used in analyzing the data obtained during the tests of October, 1920, in the attempt to correlate the fading characteristics with the weather and at-

mospheric conditions at the time of the observation. For this purpose a map was prepared for each transmitting station for each night; that is, a map for each schedule transmitted. Blank maps were used similar to those used by the Department of Agriculture for the weather maps. These maps carry an outline of the United States, with the principal rivers, and the boundaries of all States. In preparing a particular map nine rubber stamps were used. Three of these carried the letter "S" in three sizes.

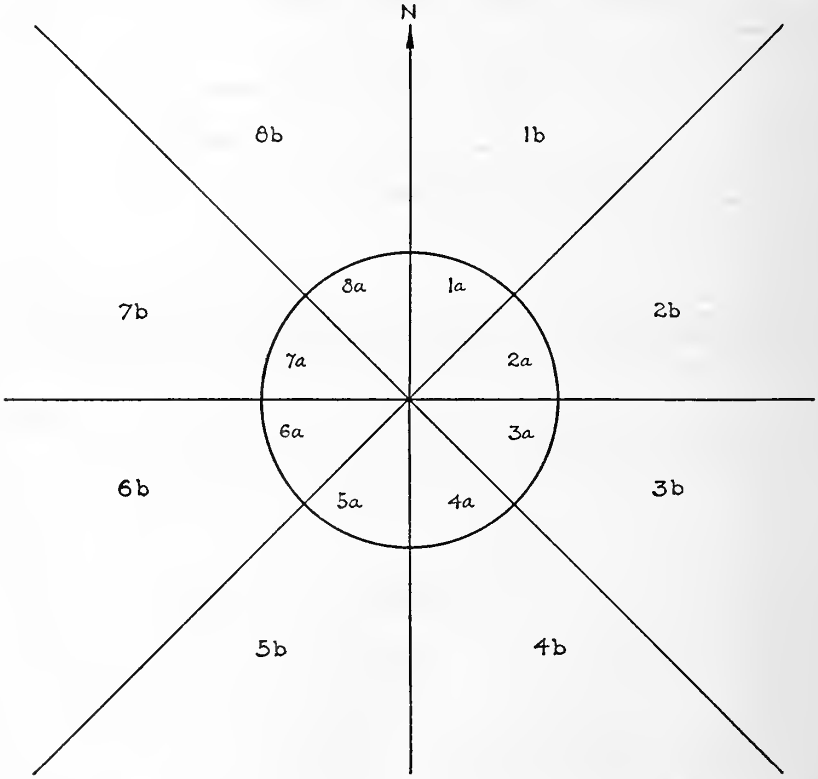


Fig. 8.—*Chart used in classifying receiving stations according to direction and distance from a given transmitting station.*

Black ink was used with this stamp, the letter "S" designating "static," and the size of the letter indicating the magnitude of the intensity of the "static" or atmospheric disturbances at each recording station for that particular observation. In the same manner three sizes of the letter "F" printed in red ink were used to indicate the magnitude or severity of fading at each observing station, and three sizes of the letter "I" printed in green ink indicated the average signal intensity at each of the recording stations for the particular observation.

In general, the letters were not printed for each individual station but where possible for the whole region. It was thus possible, by glancing at the map, to determine the directions in which loudest signals were received, the locations of the most severe and the least severe fading, and also to associate these factors with the intensity of strays. Also, by having at hand the weather map for the day of the observation, these factors could be compared with the climatological conditions, such as rain, clouds, barometric pressure and pressure gradient, and temperature and temperature gradient.

In analyzing the maps a piece of tracing cloth was prepared upon which were drawn lines dividing a circle of about 10 inches in diameter into octants. Another circle was drawn concentrically with the larger one to represent a distance of 250 miles according to the scale on the maps employed. The octants of each circle were then numbered consecutively from one to eight, as shown in Figure 8. In analysis this sheet was placed upon the map in such a way that the center of the circle coincided with the location of the transmitting station, and the general magnitudes of the signal "static" and fading intensities were noted for each of the divisions on the ruled sheet. These data were then tabulated on large sheets and analyzed by counting the number of occasions when each of the three intensities of signals, strays, and fading occurred, simultaneously, with the several weather conditions noted.

Table 1 gives the number of occasions of simultaneous occurrence of these various features of radio transmission and weather.

TABLE 1.—Summary of Fading Test Results, October, 1920, as to Weather Conditions as Obtained from Analysis of Maps.

Fading.			Signal intensity.			Strays.			Remarks.
F	F	F	I	I	I	S	S	S	
29	33	25	16	60	11	17	22	49	Transmission from region of low to region of high barometric pressure.
27	45	51	33	71	21	30	39	52	Transmission from region of high to region of low barometric pressure.
37	64	33	29	87	16	36	44	54	Transmission between regions of approximately equal barometric pressure.
50	54	46	36	92	26	41	40	75	Barometer rising at sending station.
40	48	42	31	72	30	27	34	72	Barometer rising at receiving station.
43	50	41	30	78	31	30	35	66	Barometer rising in region between sending and receiving stations.
20	21	8	9	35	5	6	10	33	Barometer falling at sending station.
22	27	14	11	43	7	12	12	38	Barometer falling at receiving station.
21	23	9	9	38	5	8	10	34	Barometer falling in region between sending and receiving stations.
33	46	40	17	82	12	18	29	70	Clouds at sending station.
37	38	31	17	75	9	23	28	51	Clouds at receiving station.
32	28	26	15	60	10	14	21	49	Clouds in region between sending and receiving stations.

TABLE 1.—Summary of Fading Test Results, October, 1920, as to Weather Conditions as Obtained from Analysis of Maps—Continued.

Fading.			Signal intensity.			Strays.			Remarks.
F	F	F	I	I	I	S	S	S	
6	3	3	4	7	1	3	1	8	Rain at sending station.
9	18	17	7	31	4	6	13	24	Rain at receiving station.
5	10	13	6	19	2	4	4	21	Rain in region between sending and receiving stations.
22	23	17	11	33	12	20	20	23	Clear weather immediately preceded by cloudiness at the sending station.
12	18	19	8	33	8	11	22	17	Clear weather immediately preceded by cloudiness at the receiving station.
6	10	9	4	16	7	6	13	8	Clear weather immediately preceded by cloudiness in region between sending and receiving stations.
24	34	24	24	46	12	17	26	43	Transmission from region of lower to region of higher temperature.
12	31	16	8	43	11	12	18	31	Transmission from region of higher to region of lower temperature.
57	76	69	46	131	26	55	62	84	Transmission between regions of approximately equal temperature.

In Table 1 the following interesting indications may be noted of a connection between fading, signal intensity and strays, and weather conditions existing at the time of transmission.

At times when the barometer is falling either at the sending station, at the receiving station, or in the region between the cases of severe fading predominate over the cases of slight fading (20, 22, and 21 compared with 8, 14, and 9). On the other hand, when the barometer is rising in any of these regions there is little difference in the number of cases of severe and slight fading (50, 40, and 43 compared with 46, 42, and 41).

During the presence of clouds at either the sending station, the receiving station, or in the region between there was practically no difference in the proportion of severe and slight fading reported (33, 37, and 32 compared with 40, 31, and 26).

The figures given in Table 1 indicate the following possible relationships between the intensity of received signals and weather conditions:

The intensity of signals transmitted along lines of equal barometric pressure is slightly greater than those transmitted either up or down the barometric gradient. (The ratios of the percentages of strong to weak signals are 1.8, 1.4, and 1.6 for transmission along isobars, up the barometric gradient, and down the barometric gradient, respectively.)

Signals are louder when clouds are present or when it is rainy at either the sending station, the receiving station, or in the intervening region. (Strong signals 17, 17, 15, and 4, 7, 6 times, and weak signals 12, 9, 10, and 1, 4, 2 times, respectively.)

The proportion of weak to strong signals is greater when transmission is from a region of higher to a region of lower temperature. (Ratios of weak to strong signals are 11 to 8, 12 to 24, and 26 to 46 in the cases of transmission down the temperature gradient, up the temperature gradient and along isotherms, respectively.)

The relations between the occurrence of strays and weather conditions indicated by Table 1 are as follows: Strays are of less severity when the barometer is falling at either the sending station, the receiving station, or in the intervening region. The ratio of the number of reports of weak "static" to the number of reports of strong "static" being approximately 4 in this case compared to a ratio of about 2 in the case of a rising barometer.

During the presence of clouds or rain a larger part of the records report weak strays rather than strong strays. (Weak strays are reported 70, 51, 49, and 8, 24, 21 times while severe strays are reported 18, 23, 14, and 3, 6, 4 times when the sending, receiving, and intermediate regions are cloudy and rainy, respectively.)

The tabulation given in Table 1 was made from the reports received from 108 individual observers. The number of cases of transmission represented (that is, from a transmitting station to a receiving region either inside or outside of the 250-mile circle and in one of the octants shown in fig. 8) was 2,141.

Table 2 shows the number of times when the several magnitudes of fading, signal intensity and strays were observed in regions within the circle drawn with a radius of 250 miles from the transmitting station and in regions outside this circle.

In Table 3 these same results are given as percentages of the number of observations of strays, signal intensity, or fading in the inner or outer zone, respectively. For example, the 75 cases of weak signals reported in zone (*a*) are 28 per cent of the total number $(75+139+50=264)$ of reports on signal intensity in this zone.

TABLE 2.—Summary of Fading Test Results, October, 1920, as to Distance.

[NUMBER OF CASES OF TRANSMISSION.]

	Fading.			Signal intensity.			Strays.		
	F	F	F	I	I	I	S	S	S
Zone (*a*) within 250 miles	66	67	54	50	139	75	51	70	95
Zone (*b*) beyond 250 miles	17	61	42	29	89	57	33	38	73

TABLE 3.—Summary of Fading Test Results, October, 1920, as to Distance.

[PER CENT OF CASES OF TRANSMISSION.]

	Fading.			Signal intensity.			Strays.		
	F	F	F	I	I	I	S	S	S
Zone (*a*) within 250 miles	35	36	29	19	53	28	24	32	44
Zone (*b*) beyond 250 miles	14	51	35	17	51	32	23	26	51

From Tables 2 and 3 it will be seen that the proportions of loud, medium, and weak signals reported from the two zones are approximately equal. This may be on account of the fact that most observers adjusted their receiving apparatus or made their records so that the curves would fall, as a whole, about on the middle of the card (fig. 2) on which the observations were being recorded.

There is also little difference in the proportion of strong, medium, and weak strays or "static" in the two zones. There is noticeably more severe fading reported from the region within 250 miles of the transmitting station than from the region beyond that distance, 35 per cent of the cases of fading within that distance being classed as very bad, while only 14 per cent of the cases of fading beyond that distance were in that class. When the signals were received at all at points farther than 250 miles from the transmitting station, the fading in 86 per cent of the cases was slight or of only moderate severity.

The maximum distance over which signals were received from the several transmitting stations differed somewhat on the different nights of transmission. Table 4 gives the average radius over which transmission took place in the case of the October, 1920, tests.

TABLE 4.—Radius of Transmission of Stations Which Sent Test Schedules During October, 1920.

Station.	Average radius.	Maximum radius.
	Miles.	Per cent.
1AW	780	60
NSF	940	75
8ZW	960	87
8ER	790	88
9ZN	900	90

The method of analysis of the results of the October, 1920, tests outlined above was very cumbersome compared with the statistical method described below in which punched cards were used. The results given above are also based on a much smaller number of observations, since records taken during the October, January, and April tests were included in the subsequent analysis using the punched cards. The conclusions which are outlined above do not in all cases agree with those indicated by the statistical analysis described below and are not to be considered as reliable as those given in connection with Tables 5 to 14. Even the latter are in some cases subject to considerable question. They are given only as indications of possible relations between radio transmission phenomena and weather conditions which are brought out by the reports received from the cooperating observers.

(*d*) Statistical Analysis.—The method used for making the statistical analysis of the data obtained employed the punched card and tabulating machine system as used by the United States Bureau of the Census. This method is capable of analyzing any amount of data with an accuracy limited only by the accuracy of the data itself. Since the method is almost entirely automatic, it is much more rapid than other methods of analysis. For a detailed description of the method employed reference should be made to a paper "Application of statistical analysis to radio transmission problems," by F. H. Engel, assistant physicist.

1. *Explanation of method.*—Briefly, the system consists of punching a card according to a tabulation of the data to be analyzed. A machine somewhat similar to an ordinary adding machine punches the card. The sorting of the cards is performed automatically by an electrically operated machine, according to any desired arrangement. When the cards are sorted, they may be counted and the percentages calculated, after which the cards may be reassembled for analysis according to another arrangement.

2. *Accuracy of results.*—The accuracy, as stated before, is limited only by the accuracy of the observations. In these tests this accuracy was undoubtedly of a rather low order, due to the personal element involved, but since such errors tend to balance out when a large number of observations are taken the final results may be considered as reasonably accurate.

V. RESULTS OF TESTS.

1. DIFFICULTIES OF INVESTIGATION.

There are many difficulties attendant to a statistical investigation of this type, largely due to the great number of persons involved and to the personal equation which enters in from many angles. The very nature of the subject under investigation and the almost countless factors that undoubtedly influence the character and behavior of the fading phenomena preclude the obtaining of anything but general results. In many cases results are unconclusive not because of the lack of accurate data, but because unconsidered factors are affecting the results.

2. CONCLUSIONS WHICH MAY BE DRAWN.

The following conclusions, with the percentage as determined by this analysis, are given as an indication that there is a tendency that the fading will be of a certain character under the given conditions. The conclusions are not positive, and it is possible that they may be reversed by the results of future investigation.

TABLE 5.—A Comparison of Results Obtained on the 250 and 375 m Wave Lengths.

Wave length.	Number of observations.	Cases of bad fading.	Bad fading.	Cases of loud signals.	Loud signals.	Cases of bad strays.	Bad strays.
			Per cent.		Per cent.		Per cent.
250	2,701	873	32.3	508	18.8	368	13.6
375	1,965	511	26.0	321	16.4	259	13.2

Observations numbering 2,701 were made on the 250-m wave length, 1,965 on the 375-m wave length, and 1,018 on other wave lengths. Of the 5,684 observations there were 990 cases of loud signals and 1,251 cases of weak signals, the remainder being reported as of medium intensity. Table 5 gives the relative occurence of bad fading on the wave lengths 250 and 375 m, and inspection will show that the bad fading is more pronounced on the shorter wave lengths. The shorter wave length is slightly conducive to a greater percentage of loud signals. There is little difference in the intensity of strays or "static" on the 250 and 375 m wave lengths.

TABLE 6.—The Effect of Barometric Conditions on Transmission.

Severity of fading.	Changing barometer.	Stationary barometer.	Up or down gradient.	Along isobars.
	Per cent.	Per cent.	Per cent.	Per cent.
None	26.2	25.0	5.1	14.7
Bad	30.6	27.0	31.4	26.6

Table 6 indicates that a changing barometer at the transmitting station does not affect the fading. This table also shows that the fading is greater when the transmission takes place up or down the barometric gradient. No difference was noted in the fading between transmission up and transmission down the barometric gradient.

TABLE 7.—Effect of Barometric Gradient on Signal Strength.

Signal strength.	Along isobars.	Up or down gradient.
	Per cent.	Per cent.
Weak	18.7	23.3
Strong	20.4	20.4

Table 7 indicates that waves which travel along the isobars produce stronger signals than those travelling up or down the barometric gradient. No difference was found between transmission up and transmission down the barometric gradient.

TABLE 8.—Effect of Temperature Gradient on Signal Strength.

Signal strength.	Up or down gradient.	Along isotherms.
	Per cent.	Per cent.
Weak	23.6	19.8
Strong	15.5	20.1

Inspection of Table 8 indicates that transmission along the isotherms is slightly more conducive to stronger signals than when transmission is up or down the temperature gradient.

TABLE 9.—Effect of Temperature Gradient on Fading.

Severity of fading.	Up or down gradient.	Along isotherms.
	Per cent.	Per cent.
None	14.5	28.6
Bad	85.5	71.4

Table 9 indicates that transmission along the isotherms tends toward less fading.

NOTE.—Transmission along the isobars is slightly less conducive to fading than transmission along the isotherms, as indicated by a comparison of Tables 6 and 9.

TABLE 10.—Effect of Clouds on Fading.

Severity of fading.	Cloudy at transmitting station.	Clear at transmitting station.	Generally cloudy.	Generally clear.
	Per cent.	Per cent.	Per cent.	Per cent.
None	7.4	8.2	26.4	29.3
Bad	31.0	29.1	30.5	21.7

Table 10 indicates that clouds at the transmitting station have no effect upon fading. It also shows that if it is generally cloudy at and between the transmitting and receiving station the fading is more likely to be bad than when it is clear.

TABLE 11.—Effect of Clouds on Signal Strength.

Signal strength.	Clouds at transmitting station.	Clear at transmitting station.	Clouds at receiving station.	Clear at receiving station.	Generally cloudy.	Generally clear.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Weak	11.6	12.2	20.8	23.2	22.2	21.6
Strong	6.3	4.9	18.0	16.8	17.5	17.2

Table 11 indicates that clouds at the transmitting station have no effect upon signal intensity. It also shows that clouds at the receiving station are conducive to stronger signals. Generally cloudy weather at and between the transmitting and receiving stations has no effect upon the signal strength.

TABLE 12.—Showing the Effects of Clouds on the Intensity of Strays.

Intensity of strays.	Clouds at receiving station.	Clear at receiving station.
	Per cent.	Per cent.
Weak	18.8	19.2
Strong	11.2	8.8

Table 12 indicates that clouds at the receiving station produce stronger strays.

TABLE 13.—Occurrence of Various Degrees of Fading.

Cases of weak signals.	Zero fading.	Slight fading.	Medium fading.	Bad slow fading.	Bad fast fading.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1,251	4.6	16.8	29.2	46.0	3.4

Table 13 gives the percentage occurrence of zero, slight, medium, bad slow, and bad fast fading. Inspection shows a tendency in weak signals to slow bad fading.

TABLE 14.—Fading and Near-by Wire Lines.

Severity of fading.	Per cent having wire lines near by.
None	47.2
Bad	46.7

Table 14 indicates that the presence of near-by wire lines has no effect upon fading.

3. PROXIMITY OF STATIONS.

In addition to these more general conclusions, some interesting information was obtained from the results of the January and April tests, in which the locations of the transmitting stations were particularly considered. In the January tests two transmitting stations in the same locality sent the same test simultaneously, but at slightly different wave lengths, the intention being to note whether the fading of these two stations exhibited any similarity. If the fading were produced by effects close to the transmitting stations, we should expect to find similar fading curves at all or many of the recording stations. Since we have already seen that similar curves occurred very rarely, we may conclude that effects near to the transmitting station contribute little to the fading characteristics at a distance or at least do not similarly affect receiving stations scattered over a considerable area.

It was found that observers within a mile or two of each other may get entirely different curves when observing a distant transmitting station. The records of the January tests show also that near-by observers obtained entirely different records of the transmission of the two special transmitting stations. In some cases the two sending stations were found to fade simultaneously, in other cases they seemed to be fading exactly inversely—that is, 180° out of phase—and in still other cases the curves obtained by near-by recorders were entirely unlike. Inasmuch as the pairs of transmitting stations of the January tests were operated on slightly different wave lengths, it was thought that there might be a possibility of dissimilar fading due to this cause. Accordingly, in the April tests the transmitting pairs were operated on the same wave length, but each with a distinctive spark note to facilitate the observation. The results of this test were much the same as the previous one—that is, the two stations failed to fade simultaneously in all cases. These observations lead to the conclusion that the cause of fading is of such a nature as to affect individually only small receiving areas.

4. RESULTS OF SPECIAL TESTS.

Two special tests were conducted during the month of October, as mentioned earlier in this paper. The sunset test, held on October 17, was intended to investigate fading during the period

of sunset. The curves obtained showed normal fading in every case, the only item of interest being the gradual increase in signal intensity as night came on.

The special noon test, held on October 24, was intended to contrast with the fading curves obtained at night. Unfortunately, very few curves were received, and these were all from points within the daylight ranges of the stations and exhibited no fading.

The third of the special tests, held on October 26 and 28, were for the purpose of locating the source of the very erratic fading of station 8XK at Pittsburgh, Pa. It was believed that tube blocking or similar trouble was causing much of the apparent fading of this station. The first tests, sent with the usual apparatus, showed the usual very rapid and severe fading, while the second test, transmitted first with the usual apparatus and immediately following with a master oscillator, power-amplifier circuit, showed definitely that the trouble was due entirely to tube blocking and was not true fading.

VI. THEORIES OF FADING.

1. ABSORPTION ALONG HEAVISIDE SURFACE.

Several theories regarding radio signal fading phenomena have been proposed. A preliminary discussion based on the results of this investigation was given by two of the authors before the Philosophical Society of Washington on January 29, 1921.[4] This theory takes account of the presence of the Heaviside surface in the atmosphere above the earth.

The idea of an upper conducting surface between which and the earth's surface electrical waves would be propagated antedates the use of radio for long-distance communication, since it was discovered by Fitzgerald in 1893 and by Heaviside in 1900. Considerations largely independent of radio phenomena suggest the following structure and boundaries of the atmosphere, as indicated in Figure 9. (*a*) The earth's surface, a relatively poor conductor. (*b*) The troposphere, about 10 km thick, within which are the causes of our meteorological phenomena, and an atmosphere similar to that which we breathe. (*c*) A radioactive layer, separating the troposphere from the region above it. (The existence of this layer is not as well established as the others, nor is its existence so important in the explanation of the radio

[4] "Radio signal fading phenomena," by J. H. Dellinger and L. E. Whittemore, Jour. of the Wash. Acad. of Sci., **11**, No. 11, June 4, 1921

phenomena.) (*d*) The stratosphere, or isothermal layer, having a thickness of approximately 100 km. The stratosphere is ionized by the sun's rays in the daytime but quickly loses this property by the recombination of the ions at night. (*e*) The Heaviside surface, permanently ionized, and an almost perfect conductor.

The boundary of the Heaviside surface is not considered as absolutely horizontal but as changing from time to time. The permanently ionized region above the Heaviside surface is the region of permanent aurora and is so good a conductor that waves can not penetrate it. Any waves reaching it can only slide along it, just as waves slide along the even less perfectly conducting surface of the earth.

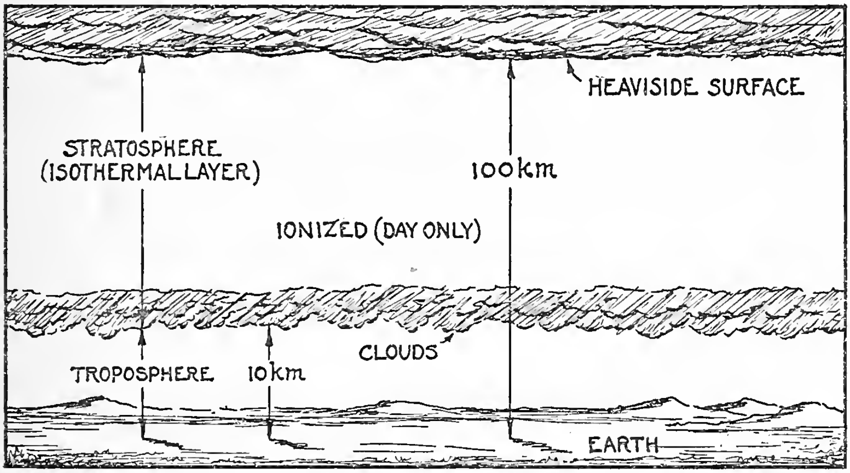


FIG. 9.—*Vertical cross section of the earth's atmosphere.*

In daylight transmission the waves can not reach the Heaviside surface because of the intervening ionized stratosphere, and hence only those waves which travel along the earth's surface are useful during the daytime. In traveling along the earth's surface the waves are diminished in intensity by absorption of their energy in the earth. At night, on the other hand, the waves may reach the Heaviside surface and travel and slide along it without appreciable absorption. As explained further below, this means that the waves travel enormous distances at night and short waves travel farther than long ones.

Because of the variable absorption which may be introduced by the irregularities of the Heaviside surface and the adjoining regions the waves may vary rapidly in intensity. Small irregularities would affect short waves more than long waves. These conclusions are in precise agreement with the facts.

Observations to date indicate that the fading is greatest for waves within a certain range of wave lengths and is less for either longer or shorter waves. Fading is more pronounced at wave lengths in the neighborhood of 250 m than at longer wave lengths. Transmission experiments using 100-m waves indicate less severe fading than on 250 m. This may give an indication of the magnitude of the irregularities of the Heaviside surface.

The relation between the size of an obstructing or absorbing mass or substance and the wave length of the waves affected is illustrated by the fact that light waves are able to pass directly through a sufficiently thin sheet (0.00001 cm thick) of any material. It is easier for a large mass of something to somewhat obstruct a 200-m wave than a 2,000-m wave.

If this theory be correct, the maximum intensity received at night should be that given by the transmission formula [5] with the absorption factor equal to unity. Tests recently reported by Nichols and Espenschied [6] substantiate this theory.

On a wave length between 350 and 400 m the intensity of signals received at night was found to vary between two definite limiting values. These values are: (1) That which would be obtained if the waves suffered no absorption, and (2) that which would be obtained with the absorption normally present in daytime transmission.

This shows that the atmospheric absorption encountered by the waves at night varies from time to time between zero and the maximum absorption obtaining at any time, namely, the daylight value. That is, the part of the wave which travels up to the Heaviside surface may be unabsorbed or it may be totally absorbed, leaving, in the latter case, only the wave conducted along the ground as effective in transmitting signals.

Thus, while the transmission formula can not predict the varying intensity of signals observed at night, it does give the limiting maximum value, and, if the daytime value of the absorption coefficient is known for the particular region over which transmission takes place,[7] it also gives a limiting minimum value.

[5] The current in a receiving antenna is given by the following expression:

$$I_r \propto \frac{1}{\lambda d} \epsilon^{-\alpha \frac{d}{\sqrt{\lambda}}}$$

where λ is the wave length, d is the distance from the transmitting station, $\epsilon=2.718\ldots$, α is a constant known as the absorption coefficient, and the quantity $\epsilon^{-\alpha\frac{d}{\sqrt{\lambda}}}$ is the absorption factor.

[6] Radio extension of the telephone system to ships at sea. Proc. I. R. E., **11**, p. 193, June, 1923.

[7] The value of this absorption coefficient has been determined by Austin (B. S. Sci. Paper, No. 159; 1911) for daytime transmission over sea water to be 0.000047 when d and λ are both expressed in meters.

Within the distance from a transmitting station in which ground absorption is negligible there is no fading and the day and night intensities are equal, since the waves are not affected by conditions in the upper atmosphere.

A preliminary statistical study of the transmission range of certain broadcasting stations which has been made since the work described in this paper was done indicates that at a distance of the order of 150 miles from the transmitting station a noticeable decrease is observed in the signal intensity, which increases again for greater distances. The distance at which this occurs varies with the wave frequency, which suggests that its explanation is associated with the variation of ground absorption with wave frequency, and that the signals received at distances beyond this minimum point are due to the propagation along the Heaviside surface. Further tests of a similar nature should throw more light on this phenomenon.

2. REFLECTION AND INTERFERENCE.

Another theory of fading has been proposed by one of the authors and was discussed in a paper presented at the meeting of the Radio Club of America, in New York, on September 24, 1920.[8] This theory is based upon the principle of the production of interference bands in the vicinity of the receiving station by the reflection of the waves from any reflecting surface, such as a cloud or fog bank or from the Heaviside surface or other ionized surface. The movement or shifting of this reflecting surface or series of reflecting surfaces would result in the movement of the interference bands at the receiving station and the production of the fading phenomenon. We should expect cloud and fog banks to reflect short waves more than long waves, since such banks are more nearly comparable in size with the shorter wave lengths.

3. CHANGES IN DIRECTION.

Other theories have been proposed from time to time by many people, the majority of the theories agreeing in principle with those just described. It has been suggested that fading may be influenced by changes in the direction from which the waves arrive at a receiving station, and consequently a highly directional receiving antenna would experience an apparent fading of signals due to direction changes that a nondirectional receiving antenna would not. Experiments conducted at Anacostia, Washington,

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[8] The Bureau of Standards ARRL tests of short wave radio signal fading, S. Kruse, QST, 4, 16· December, 1920.

and Chicago during the fading tests indicate that direction changes of the short waves here considered are negligible, however, and that they do not enter into the causes of fading.[9]

VII. ACKNOWLEDGMENTS.

The authors desire to acknowledge most heartily the assistance rendered by the officers and members of the American Radio Relay League in carrying forward these tests. The tests would have been impossible without the cordial cooperation of the 17 transmitting operators and nearly 250 receiving operators who gladly volunteered their services. The work has given results not only in the form described in this paper, but in the way of experience which is of value in organizing tests on the transmission range of radio stations.

Special acknowledgment is due to F. H. Engel and H. C. Forbes for their work on the statistical analysis of the records and the compilation of the paper in its present form. Other members of the Bureau of Standards staff who have assisted in the work are F. M. Baer, H. M. Shaffer, M. S. Strock, and E. B. Shea.

VIII. SUMMARY.

The results of the statistical study of fading are given in the tables and discussion above. Some of the principal conclusions are shown in the following table:

	Fading.	Signal intensity.
Wave length	Slightly more fading at shorter wave lengths.	Slightly stronger signals at shorter wave lengths.
Barometric pressure	More fading when transmission is up or down barometric gradient.	Stronger signals when transmission is along isobars.
Temperature	Slightly more fading when transmission is up or down temperature gradient.	Stronger signals when transmission is along isotherms.

The observations reported are generally consistent with the hypothesis that fading is caused by variations in the absorption of radio waves as they travel along the Heaviside surface. Fading and very great transmission distances with short waves occur only at night, because in the daytime the waves do not reach the Heaviside surface. The variations are apparently so local in their character that the transmitting or receiving area over which the fading is uniform is very small, indeed.

WASHINGTON, April 12, 1923.

[9] In this connection, see the following: Variation in Direction of Propagation of Long Electromagnetic Waves, by Lieut. Commander A. Hoyt Taylor, B. S. Sci. Paper No. 353. Radio direction changes and variations of audibility, by Carl Kinsley and Albert Sobey, Proc. I. R. E., 8, pp. 299–323, August, 1920.

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